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Environmental impacts of floating solar panels on freshwater systems and their techno-ecological synergies

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E-mail: s.midauargondimrocha@lancaster.ac.uk**Keywords:** floatovoltaics, floating solar panels, hydrodynamics, water quality, techno-ecological synergiesSupplementary material for this article is available [online](#)**Abstract**

Renewable energy sources, such as floating photovoltaic systems (FPVs), are crucial to mitigating the climate crisis. FPV deployments on freshwater bodies are rapidly growing, as they avert land-use change, operate with increased efficiency, and potentially improve water availability by reducing evaporation and the frequency of algal blooms. However, understanding of the ecological consequences for water bodies is very limited despite the variable and far-reaching range of potential impacts. Here, we bring novel insight by combining an established theoretical approach—techno-ecological synergies (TES)—with robust understanding of water body functioning, to direct sustainable FPV deployments. Specifically, we show the potential to integrate consideration of both energy and ecological systems for FPV deployment decisions based on current evidence and fundamental understanding of freshwater body states and processes. Based on 422 pieces of evidence from a systematic review of known physical ($n = 283$), chemical ($n = 96$) and biological ($n = 43$) effects of FPV on freshwater systems, we outline eight potential TES that could be realised through FPV location, design, and operation decisions. There was most evidence ($n = 114$) for the Water Use Efficiency TES, which all reported decreased evaporation rates, or increased water savings, due to panel shading. We highlight a lack of understanding of chemical and biological effects of FPV on hosting water bodies, as well as a need for comprehensive studies in which physical, chemical, and biological aspects of water body dynamics are integrated. Finally, we detail research priorities to ensure future FPV deployments bring benefit for both energy and water bodies. Ultimately, integrated energy and water body system knowledge, FPV deployments could mitigate both the climate and ecological emergencies, with notable benefits for society.

1. Introduction

Decarbonisation of the energy generation sector is a key focus of the global response to the climate crisis (Namin *et al* 2023, Garrett *et al* 2024). Use of fossil fuels for energy generation is predicted to decrease sharply to a 12% share of the global total by 2050 (DNV 2022). In contrast, solar photovoltaic (PV) energy generation is predicted to grow 20-fold by 2050, constituting 38% of global supply (DNV 2022). The anticipated domination of PV is due to its cost competitiveness (IRENA 2022), and flexibility in deployment in terms of scale and mounting (i.e. ground, building or water) location.

Water-mounted, or floating PV systems (FPVs), are a relatively new means of deployment, and are growing rapidly in number and scale across the world (Horton 2022, YSG Solar 2022). They typically comprise floats (either continuous rafts or a pontoon-based system with racking), a mooring or anchoring system, inverters, transmission cables and the PV modules (World Bank Group, ESMAP and SERIS 2019).

From an energy perspective, they tend to be 10%–15% more efficient and longer lasting than their terrestrial counterparts due to cooling by the water (Sacramento *et al* 2015, Liu *et al* 2018, Elminshawy *et al* 2024), and have lower maintenance costs (World Bank Group, ESMAP and SERIS 2019). Moreover, deploying FPVs on hydroelectric power reservoirs improves the power curve and saves grid connection costs (Haas *et al* 2020, De Campos *et al* 2021, Gonzalez Sanchez *et al* 2021).

Whilst the technical benefits of FPVs are relatively well understood, the environmental implications, which may be both beneficial and detrimental, to the host water body are less well resolved (Gorjian *et al* 2021, Nobre *et al* 2023, Benjamins *et al* 2024). An example of the complexity of host waterbodies' responses is given by Ilgen *et al* (2023), who investigated how an existing FPV plant affected a German reservoir's thermal structure, including innovative spatial assessment of radiation under the panels, and evidenced a non-linear relationship between increased FPV coverage and decreased water temperature. However, knowledge advancements are urgently needed, extending beyond effects on water temperature, given the potential implications for the critical ecosystem services provided by water bodies, including food provision (e.g. aquaculture and fishing), biodiversity, potable water and recreation. It is broadly accepted that evaporation losses are reduced, especially in arid and semiarid environments, with positive implications for water availability (Spencer *et al* 2019, Armstrong *et al* 2020, Exley *et al* 2021a, Elminshawy *et al* 2024). Specifically, Elminshawy *et al* (2024) combined modelling and experimental tests in arid Egypt to compare how different tilting angles affect evaporative losses in the reservoir, finding reductions between 58% and 83%. However, resolution of FPV effects on the full range of physical, chemical and biological properties and processes is challenging as the outcomes are highly contingent upon FPV designs, water body characteristics, deployment location, and climate regime (Armstrong *et al* 2020).

The development of a predictive understanding of FPV impacts on water body chemistry (including nutrients) and biology is challenging as it depends strongly upon ecosystem properties and the scale of both the reservoir and the FPV plant. For some variables, including dissolved oxygen (DO) concentrations (Château *et al* 2019, Ma *et al* 2021) and plankton concentration (Li *et al* 2023) lower overall concentrations are typically observed. In contrast, the effects of FPV on other parameters vary. For example, total phosphorus concentrations have been observed to increase (Château *et al* 2019, Yang *et al* 2022, Liu *et al* 2023), decrease (Li *et al* 2023), and be unimpacted (Wang *et al* 2021, Ziar *et al* 2020). Likewise, nitrogen responses vary (Château *et al* 2019, Li *et al* 2020, Ziar *et al* 2020).

The complexity of changes in water body functioning in response to the direct, indirect and interactive effects of FPVs on processes, and the pivotal role of thermal stratification, complicate our ability to predict consequences. A rapidly growing number of studies have emerged recently to tackle this gap, but these have largely been at individual or a small number of sites. There is a need to integrate these findings, and identify common trends and key knowledge gaps in order to provide evidence to inform future FPV deployments. To date, syntheses have been hypothesis-based (Sahu *et al* 2016, Abid *et al* 2019, Armstrong *et al* 2020, Ma *et al* 2021, Essak and Ghosh 2022) or focused on a range of water body covers that may act as analogues for FPV, i.e. shade cloth, vegetation and ice (Exley *et al* 2021b).

Given the rapidly accelerating number of FPV systems and degraded state of freshwater bodies across the world, deploying FPV in a way that enhances the ecological state and function of the host water bodies, and the critical ecosystem services they provide to society is attractive. A techno-ecological synergies (TES) framework identifies opportunities for mutually beneficial relationships between technological and ecological outcomes in the recipient environment, aiming to boost sustainability for system functioning. Consequently, taking a TES approach to FPV deployment decisions will promote desirable energy system and ecosystem outcomes. Potential TES of FPVs include air pollution reduction, climate regulation, energy equity and/or security, fuel diversity, food system resilience, grid reliability and/or resilience, human health and wellbeing, land sparing, PV module efficiency, water use efficiency, and water quality (Hernandez *et al* 2019). These consequences can occur at the deployment location or elsewhere, immediately or through time, and range from the local to global scale (Hernandez *et al* 2019).

Given the accelerating climate and ecological emergencies and pace of FPV deployment, this study aims to establish the potential TES that could be realised through informed FPV location, design and deployment decisions, based on existing scientific understanding of water body responses to FPVs and fundamental understanding of water bodies' states and processes. Specifically, we (1) identify the TES that could be realised through FPV location, design, and operation decisions at the waterbody scale, (2) establish, via a systematic review of literature, the current evidence for whether FPV impacts on ecological states and processes are likely to lead to the realisation of those synergies, and (3) outline future research priorities to enable TES of FPV to be maximised. Therefore, we bring novelty by combining an established theoretical approach with robust understanding of water body functioning, allowing us to map current knowledge on FPV impacts and direct the sustainable development of this technology.

2. Methods

2.1. TES

The potential TES considered were taken from Hernandez *et al* (2019). Those which could be influenced by FPV location, design, and operation decisions were identified through fundamental understanding of water body function. FPV location captures various water body characteristics that may influence their responses to FPV deployment, for example, depth, nutrient concentration, and climate context. FPV design factors that may influence water body response critically include the percentage of coverage but also other factors such as whether the support structure is a continuous float or a non-continuous pontoon, and how it is tethered. Finally, operation considerations include aspects such as how the FPV is cleaned and whether it is moved around the waterbody over its lifetime.

2.2. Current evidence mapping

To assess the current evidence regarding the impacts of floating solar panels on freshwater systems, a systematic review of the scientific literature was conducted, following the approach of Page *et al* (2021).

Firstly, the scope of the review was delineated using the population, intervention, comparison and outcome elements of the primary question, 'What is the current evidence for impacts of floating solar panels on freshwater systems?'. The population was defined as freshwater systems that host FPVs encompassing 19 unique water body terms (SI 1 table S1). Marine systems, even though increasingly reported as FPVs hosts, were not included in this review given the lack of published studies, and the different environmental drivers compared to freshwater systems, making their dynamics incomparable. The intervention was the presence of FPVs, including 10 variants of this term (SI 1 table S1). No comparison or outcome was defined given the infancy of the research topic and to reduce the risk of omitting relevant studies.

The search was conducted in Web of Science and Scopus using search strings derived from the population and intervention terms and limited to English language documents (i.e. journal, conference proceedings or book chapter), hereafter called articles. Publications dated 2000 to present were included, and no constraint on geographical location was applied. Unrelated subject areas were excluded, such as medicine, veterinary science, and nursing. Boolean operators 'AND' and 'OR' were used to combine the keywords (table S1). The search was conducted on 3rd November 2022 and the exact same search and procedure re-run from 3rd November 2022–26th July 2024 to update the review.

The articles returned from the search were compiled into the reference manager EndNote, in which an initial screening was performed by reading the article's title to identify duplicated and unrelated articles. The abstracts of the remaining papers were read and any that were irrelevant removed. The final set of articles were read in their entirety and irrelevant articles removed. Additionally, a 'snowball' search (Greenhalgh and Peacock 2005) was conducted to find relevant studies cited by the final set of articles.

Secondly, an evidence database was compiled by extracting information from all the relevant articles identified from the systematic review and snowball search (table 1). General information on the paper was recorded, such as their digital object identifier or link to website, article type (journal, conference proceedings or book chapter), whether the study was a review or primary research, and if primary research the evidence type (empirical, modelled or both). If documented, information about the location, water body features, study design, sampling design, FPVs structure characteristics, and environmental parameters were recorded in the database (table 1). For information that was not documented in the article, such as the climate zone, we used the details in the paper to gather the information from other sources (see SI 1, table S2).

Given the among-study variability in measurement campaigns, that is, measurement or sampling location within the water body (e.g. top and deeper layers water temperature), and specific measures (e.g. plankton concentration and biomass), parameters were combined into categories to reduce dimensionality (see SI 1 table S3 for full details). If an article contained evidence of more than one parameter or multiple FPVs (either by using multiple tanks or water bodies for empirical studies or by applying multiple scenarios for modelling approaches), we considered these unique pieces of evidence.

2.3. Analysis of evidence

The evidence database was used to summarise current knowledge, including the overall characteristics and geographical distribution of FPV studies, the evidence type, and the direction and magnitude of FPV impacts. Chi-squared tests were used, where there were sufficient data to assess whether the FPV impacts were statistically significant (compared to there being, on average, no effect). Specifically, to apply the test, the number of pieces of evidence for each variable (e.g. temperature) had to be at least five times the number of impact categories (i.e. increased or decreased) (McHugh 2013). Finally, evidence gaps, identified by interpreting the articles from the systematic search, were used to establish future research priorities.

Table 1. Evidence of the impacts of floating photovoltaic systems on freshwater systems that was registered from the articles included in this study. The complete evidence database is provided as an MS Excel file in supplementary information 2.

Section	Extracted evidence
Location	Hemisphere; country; coordinates; Koppen–Geiger climate region (Kottek <i>et al</i> 2006); lake thermal region (Maberly <i>et al</i> 2020)
Water body features	Site name; water body type—dammed, mining pit, tank, irrigation, fish pond, canal, lab scale or wastewater pond; water type—brackish or freshwater; if it is a hydropower reservoir; surface area; capacity; maximum and mean depth; thermal structure; trophic state.
Comparison among lakes	Number of lakes evaluated; whether a comparison between lakes with and without FPV was performed; whether a comparison between current and future FPV cover was performed; whether the study has before and after FPV data.
Field campaigns	Measurements period; whether more than one season was included; how much time before FPV was evaluated; sampling frequency; whether multiple sampling points were included; whether the measurements were depth resolved.
FPV plant information	Design type; plant capacity; construction material; location on the water body; floater type; plant area; percentage of coverage.
Societal impacts	Whether it was investigated; whether community surveys were conducted; direction of the impact.
Environmental parameters measured	Whether the following variables were investigated: solar radiation, evaporation, conductivity, salinity, pH, dissolved oxygen, water temperature, oxidation–reduction-potential, stratification, light & transparency, sediment resuspension, suspended solids, plankton, nutrients, total dissolved solids, total organic carbon, biological oxygen demand, total photosynthetic pigments, contaminants, and fish. FPV impacts on each environmental parameter: direction, such as increase and decrease, and magnitude of the changes after FPV.

3. Results and discussion

3.1. Water body TES

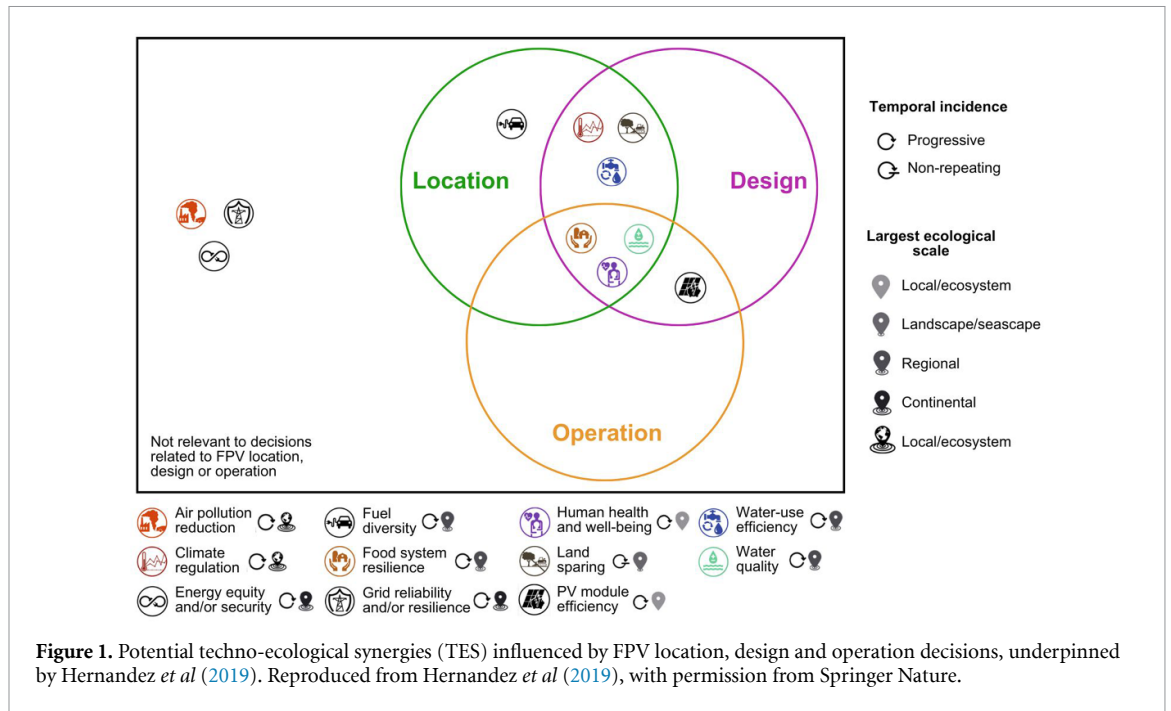
We found that eight TES, of the eleven identified by Hernandez *et al* (2019), are modulated by water body location (7), FPV design (7), FPV operation (4), or a combination (figure 1). We found that three are not directly related to ecological impacts within the host water body itself (figure 1).

3.2. Evidence to support the potential for TES

In total, there were 422 pieces of evidence that enabled us to infer potential outcomes for each of the eight TES potentially impacted by FPV location, design and operation decisions, unpinned by physical ($n = 283$), chemical ($n = 96$) and biological ($n = 43$) impacts of FPV. Below we draw on this evidence, to infer how FPV deployments could result in positive energy and ecological outcomes.

3.2.1. Climate regulation

There is scope to address climate regulation when choosing where to locate and how to design FPV, given the potential implications for water body temperature and GHG emissions. Here, we focus our discussion on temperature regulation. Under climate change, water body temperatures are rising (Schneider and Hook 2010, O'Reilly *et al* 2015, Woolway *et al* 2020), but significantly more evidence supports the notion that FPVs cause reductions in water temperature ($\chi^2 = 10.67$, $p < 0.001$, SI 1 table S4). Although, the effect of FPVs on temperature regimes of deeper water is less conclusive than that of near-surface water temperature. Specifically, 23 pieces of evidence presented the temperature response in surface water and five in deeper waters. In the surface waters covered by FPVs, the temperature generally decreased ($n = 17$). One study observed no impact of FPV on water temperature (Ziar *et al* 2020) while another observed a variable response, where no difference was noted during winter and temperatures were on average lower compared



with the control site without FPVs for spring and summer (Wang *et al* 2021). Forty percent ($n = 2$) of FPVs pieces of evidence that presented temperature in deeper waters observed a reduction in temperature, with the other three studies reporting no change, uncertainty, and an increase.

The FPV-driven decrease in surface water temperature, for example the 1.4 °C cooling observed over summer in a mining reservoir covered with FPV (Liu *et al* 2023) and the significantly lower daily averaged water temperature of aquaculture ponds covered with FPV compared with a control system without coverage, again in the order of 1.0 °C (Wang *et al* 2021), may provide local opportunities to offset the impacts of climate change temperature increases, especially as surface warming of inland water bodies globally has increased rapidly since 1985 (Woolway and Merchant 2019, Exley *et al* 2021a, Ji *et al* 2022, Schneider and Hook 2010, Vincent *et al* 2012). Woolway and Merchant (2019) analysed 635 lakes around the globe under different climate change models, and projected their surface water to increase by a median of around 2.5 °C. There is scope to control water temperature changes by varying the surface coverage of FPV as the reduction in water temperature is associated with the reduction in solar radiation receipts by the water body. Moreover, the design of the FPV can modulate impacts on the air and heat fluxes underneath the panels, and ultimately water temperature response (Exley *et al* 2021a). For example, designs that trap a confined layer of air under the panels can cause that air to heat, leading to higher temperatures in the surface water (Yang *et al* 2021, 2022).

To date, impacts of FPV on GHG emissions are unknown. However, given GHG emissions from reservoirs are positively correlated with surface water temperature (Rasilo *et al* 2015), it is possible that the reduction in surface water temperature caused by FPV could lead to a reduction in GHG emissions, resulting in a larger scale climate regulation feedback. However, further investigation of GHG emissions' full complexity is needed to support understanding of FPV impacts.

3.2.2. Fuel diversity

Diversity in fuel supply is beneficial for energy system resilience. FPVs could offer increased resilience if deployed on hydropower reservoirs, in addition to other synergistic benefits, including reduced costs, through sharing the grid connection and an improved power curve. An enhanced power curve can be obtained by optimising the operation of the hydro turbines according to FPV energy production. Specifically, this would involve exporting FPV generated electricity during the day and hydropower at night and during the day when the FPV is limited. This hybrid operation could potentially reduce renewable energy intermittency generation (Mamatha and Kulkarni 2024). Moreover, when coupled with hydropower reservoirs, FPV-induced water savings can generate more energy from those plants (De Campos *et al* 2021, Gonzalez Sanchez *et al* 2021, Alhassan *et al* 2023). For example, Venturini *et al* (2024) found a rise of 391% in the electricity production from an Italian hydropower plant when coupled with an FPV plant, while Mamatha and Kulkarni (2024) found that a hydro plant capacity factor would grow by an average of 18.4% when coupled with FPV.

3.2.3. Food system resilience

As food supply concerns increase in response to climate change and increasing and changing demand, identifying means to enhance resilience is critical. Freshwater bodies supply an array of food including fish, molluscs and vegetables, and many countries depend on freshwater fish for diets and livelihoods (Viridin *et al* 2023, Zhao *et al* 2024). Consequently there is an opportunity to tackle food system resilience when choosing where to locate, and how to design and operate FPVs. Indeed, integrated FPV-aquaculture systems have been suggested (Pringle *et al* 2017). There is little understanding of the potential of integrated FPV-food systems, but increasing evidence on combined crop or grazing PV systems on land points to beneficial outcomes (Adelhardt and Berneiser 2024, Biró-Varga *et al* 2024, Chopdar *et al* 2024). Understanding FPV impacts on fish, and therefore the realisation of this TES, is especially challenging as they are at a high trophic level and therefore are potentially sensitive to ecological changes caused by FPV coverage propagating through the food web (e.g. changes in phytoplankton, algae). These resulting emergent impacts are poorly understood with little and conflicting evidence (see SI 1 table S4) (Château *et al* 2019, Li *et al* 2020, Wang *et al* 2021).

To date, there is insufficient evidence to conclude whether FPV effects are positive or negative for food production, or provide clarity about how such effects may vary with water body characteristics. FPVs can affect fish appetite, fish production, and fish growth. For example, fish appetite under FPV arrays has been reported to increase during winter and decrease during summer (Château *et al* 2019), and alternating patterns have been observed as FPV percentage coverage increases (Li *et al* 2020). The mechanisms that cause the changes are associated with effects on habitat quality, specifically temperature dynamics, oxygen concentrations and food availability. There is potential for FPVs to improve habitat quality, but also reduce it. For example, if FPVs reduce DO concentrations it can be harmful to fish populations (Arend *et al* 2011, Rao *et al* 2014).

3.2.4. Human health and well-being

Given both the natural evolution of water bodies towards more eutrophic states over time, and rising anthropogenic nutrient loads from many catchments, the potential increased occurrence of toxic algal blooms is threatening human health and well-being (Carmichael 1994, Carmichael and Boyer 2016, Huisman *et al* 2018, Hou *et al* 2022). Thus, optimal consideration of FPV location, design, and operation could be a tool to help address increasing toxic algal blooms and promote ecological benefits in certain water bodies. Current evidence on FPV impacts on the water column consistently reports fewer or lower magnitude algal blooms due to shading from the panels (Haas *et al* 2020, Abdelal 2021, Exley *et al* 2022), emphasising the potential desirable outcome of this synergy. For example, Château *et al* (2019) found reduced average chlorophyll-*a* concentration in both summer and winter for fish ponds with FPV compared to those without. Moreover, similar results were reported for zooplankton in mining reservoirs, although species diversity increased (Li *et al* 2023). However, given the multitude of mechanisms by which FPV could effect human health and well-being, and the characteristic complex and non-linear response of water bodies to FPV, assessment need to consider the full suite of outcomes for each water body.

3.2.5. Land sparing

Growing land use pressures, due to increasing populations, and demand per capita is exerting pressure on ecological systems. Deploying FPV on water bodies may avert land-use and land-cover change with implications for nature and potentially terrestrial food production. For example, a winery in the US innovatively spared valuable land by deploying FPV on their irrigation pond, which, coupled with a ground-mounted system, transitioned all the energy consumption to renewable-powered (Far Niente *n.d.*). However, to date there has been no quantification of the land-sparing benefits of FPVs. Those are potentially anticipated as, for example, more land availability for food production, housing or environment recovery, which will depend on local constraints.

3.2.6. PV module efficiency

FPV deployment in warmer climates generally enhances FPV TES, by increasing the general power production of FPV compared to ground-mounted systems due to water cooling (Sacramento *et al* 2015, Sahu *et al* 2016, Liu *et al* 2017). These gains of FPVs related to land-based PV have been found to be around 10% in warmer climates (Sacramento *et al* 2015), whereas in colder regions they are only around 2% (Liu *et al* 2017).

3.2.7. Water use efficiency

The water-use savings FPV TES is among the most well supported, with all existing scientific evidence ($n = 114$) from both modelling and empirical studies reporting decreased evaporation rates, or increased water savings, due to panel shading. The magnitude of reductions in evaporative losses due to FPVs are

site-dependent, and the impact on water scarcity is affected by other characteristics of each site (Rodrigues *et al* 2021, Rocha *et al* 2023).

High FPV coverage scenarios could influence the hydrological cycle more broadly, resulting in a range of outcomes. The effects are likely to be complex and indirect, with reduced evaporation generally causing a dryer atmosphere and subsequently affecting rainfall events (Barry and Chorley 2009, Zhou *et al* 2021). FPV with larger footprints are also likely to cause bigger impacts on water body biological, chemical, and physical dynamics, although this is highly dependent on FPV design (Haas *et al* 2020, Exley *et al* 2021, 2022, Andini *et al* 2022, Ji *et al* 2022). There is potential for both desirable and undesirable outcomes, with higher coverages likely to be beneficial for dry regions since they tend to experience water stress conditions more commonly (Lopes *et al* 2020).

3.2.8. Water quality

Deployment of FPVs may offer TES with respect to water quality, especially through the potential for imposing growth limitations on phytoplankton communities, and therefore algal blooms. This potential synergy is, however, complex, depending upon interacting physical, chemical, and biological waterbody states and processes. Decisions on the location, design, and operation of FPVs are likely to moderate these underpinning ecosystem impacts, and thus influence the realisation of this potential synergy.

3.2.8.1. Physical aspects

Physical waterbody impacts of FPVs underpin potential climate regulation and water use efficiency synergies, as described above, but further synergistic effects may arise through impacts on thermal stratification and mixing. This is because the duration and intensity of thermal stratification influences phytoplankton growth (and therefore water quality) through effects on light limitation, sinking and buoyancy rates, and water column nutrient cycling (Ross and Sharples 2008, Longhi and Beisner 2009, Exley *et al* 2022). There is a potential opportunity for the physical impacts of FPV to enhance the water quality TES, but the realisation of this potential is likely to be highly dependent on the study site's location in addition to the plant design, and to vary seasonally.

At present, understanding of FPV impacts on stratification strength and duration ($n = 9$) and thermocline depth ($n = 3$) is limited. Consequently, FPV impacts on stratification are uncertain but impacts on water column stability patterns depend on the FPV coverage extent. Modelling studies have shown that higher coverages lead to shorter stratification duration and shallower mixed layer depth (Exley *et al* 2021a) as a consequence of lower water temperature followed by later stratification onset. On the other hand, alternating patterns depending on the mixing conditions were reported by Ji *et al* (2022) in a temperate climate hydropower reservoir, and Yang *et al* (2022) noted increased thermal stratification in a tropical dammed reservoir after FPV deployment. Effects of FPVs on stratification are also site-specific. For example, small temperature differences in warmer lakes cause higher density gradients than the same differences in colder lakes (Dingman 2015, Rocha *et al* 2022), and the cooling caused by FPV shading may have larger impacts on stratification at low latitudes.

3.2.8.2. Chemical aspects

Mechanisms underpinning water quality TES could also occur through a suite of chemical processes that will respond in complex, interactive ways to FPV deployment, design, and operation. Given that FPVs do not change catchment processes, and thus fluxes of water and materials to the waterbody from the surrounding landscape, its effects on water chemistry act through in-waterbody processes, i.e. primarily through changes to the water column's physical properties. Therefore, water body characteristics will influence chemical responses to FPVs.

Most of the evidence found in the literature documents impacts of FPVs on phosphorus ($n = 21$), nitrogen ($n = 20$) and DO ($n = 18$) concentrations. Phosphorus is frequently a limiting nutrient for primary production, a key element in water body eutrophication, and a major indicator in statutory water quality monitoring (Vollenweider 1975, Chapra and Canale 1991, Bormans *et al* 2016). As such, an understanding of phosphorus dynamics is essential to water quality TES, especially when considering algal blooms. The phosphorus concentration in the water column is dependent on both external and internal sources (Bormans *et al* 2016, Doan *et al* 2018, Olsson *et al* 2022), and deep-water anoxic conditions are associated with considerable internal phosphorus loading from the sediment (Moura *et al* 2020, Lima Neto *et al* 2022). Stratification of the water column, itself sensitive to FPV deployment, plays a role in maintaining deep water anoxia, and thus phosphorus release, which is related to its fractional composition and reservoir age (Moura *et al* 2020). Phosphorus release from sediment is also positively correlated with chlorophyll-a concentration, wind speed, and trophic state (Rocha and Lima Neto 2022).

Phosphorus response to FPVs are variable, with more studies quantifying increases ($n = 10$) than decreases ($n = 5$), although no significant difference was found ($\chi^2 = 1.67$; $p = 0.20$). FPV impacts on a range of P fractions (e.g. total, soluble reactive, organic fractions) have been assessed by several studies, but there was insufficient reporting of the specific impacts on each fraction to allow comparison among them. Studies that analysed phosphorus were conducted in shallow lakes, ponds, or pilot study tanks.

The availability of nitrogen, as well as its ratio to phosphorus concentration and form (e.g. nitrate, nitrite, ammonium, organic fractions) will also determine the nature of nutrient limitation for phytoplankton growth (Smith 1983, Wu *et al* 2022), and therefore the potential for TES associated with reductions in phytoplankton blooms. Consequently, FPV impacts on nitrogen cycling are important to understand, but are currently uncertain and complex to predict. Like phosphorus, nitrogen concentrations and fractionation are also affected by a complex interplay between waterbody hydrodynamics, chemical conditions (e.g. oxygen concentrations), consumption, transfer, production through aquatic food webs (including microbial communities), and atmospheric fixation. There was no consistent trend in the impacts of FPVs on nitrogen concentrations and studies vary greatly in the nitrogen fractions investigated, with insufficient reporting of each fraction to allow comparison. When comparing increases ($n = 7$) and decreases ($n = 7$) in nitrogen concentration after FPV deployment, no significant difference was found ($\chi^2 = 0$; $p = 1$). Wang *et al* (2021) and Ziar *et al* (2020) reported no changes in the nitrogen concentration after FPV deployment. Li *et al* (2020) found diverging impacts for different nitrogen fractions, as ammonia–nitrogen showed decreased concentration in higher FPV coverage scenarios, while nitrite–nitrogen concentrations increased.

DO concentration has cascading effects throughout the ecosystem, and is relevant to the water quality TES through its impacts upon phosphorus mobility in the water column (Moura *et al* 2020, Wang *et al* 2022) and therefore the potential for phytoplankton growth. However, FPV impacts on oxygen concentration is challenging to resolve as it is strongly and directly influenced by photosynthesis and respiration (Townsend 1999, Misra *et al* 2011, Correa-González *et al* 2014), water temperature (Paulsson and Widerlund 2023), and mixing conditions. Additionally, in reservoirs with pronounced phytoplankton blooms, decomposition processes consume and deplete oxygen (Misra *et al* 2011, Exley *et al* 2021).

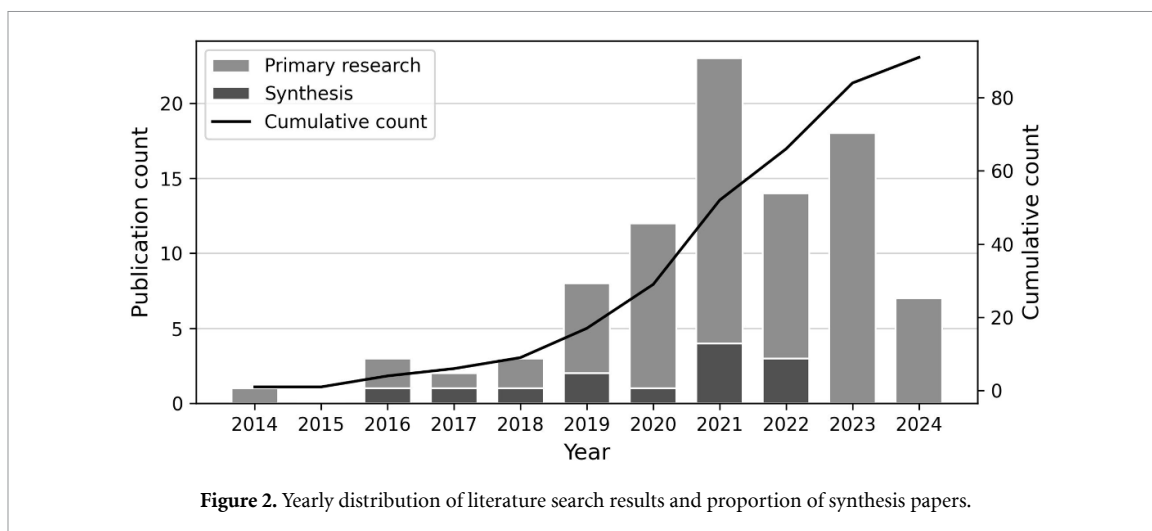
Current evidence suggests that DO concentrations generally decreased after FPV deployment ($\chi^2 = 9.31$; $p = 0.002$, $n = 1$ for an increase, $n = 12$ for a decrease). This high level of consistency may suggest that reduced light penetration, caused by FPV shading, reduces photosynthesis comparatively more than respiration. The tendency towards declining oxygen concentrations poses a risk to the realisation of water quality TES given the relationship between anoxia and internal phosphorus release. Of the 13 of the studies focussed on DO (Château *et al* 2019, Baradei and Sadeq 2020, Li *et al* 2020, Liu *et al* 2020, Ziar *et al* 2020, Al-Widyan *et al* 2021, De Lima *et al* 2021, Popa *et al* 2021, Santos *et al* 2022, Wang *et al* 2021, Andini *et al* 2022, Yang *et al* 2022, Atikah *et al* 2024, Li *et al* 2023, Liu *et al* 2023), 11 were based on empirical data, two on modelling, and one combined empirical and modelling data.

Finally, whilst other chemical parameters have been assessed, there is insufficient evidence to allow any generalised insights regarding the impact of FPV.

3.2.8.3. Biological aspects

Phytoplankton growth, and the potential for algal blooms, are important measures of biological water quality, and therefore key to water quality TES. FPV location, design, and operation can be expected to impact the growth of phytoplankton, for example through light limitation imposed by shading, with many studies highlighting opportunities to control potentially harmful blooms through FPV deployment (Haas *et al* 2020, Abdelal 2021, Exley *et al* 2022). However, phytoplankton growth is influenced by multiple factors (Interlandi and Kilham 2001). Resource availability is of great importance, including absolute concentrations of nutrients (Sun *et al* 2023) and their stoichiometric ratios (Nankabirwa *et al* 2019, Wu *et al* 2022), as are physical states and processes, specifically water temperature, stratification and mixing conditions.

Phytoplankton responses to FPV were the most frequently investigated biological variable in the literature reviewed, including plankton concentration and biomass ($n = 30$). All of the evidence, from both modelling and empirical studies, reported a decrease in indicators of phytoplankton concentration after FPV deployment (Château *et al* 2019, Baradei and Sadeq 2020, Haas *et al* 2020, Li *et al* 2020, Liu *et al* 2020, Ziar *et al* 2020, Abdelal 2021, Santos *et al* 2020, Wang *et al* 2021, Exley *et al* 2022, Yang *et al* 2022). This is consistent with the expectation that FPV shading inhibits photosynthesis by phytoplankton. However, impacts of FPV deployment are species-specific, with implications for phytoplankton diversity and community composition and subsequently for trophic interactions and the wider food web, e.g. zooplankton abundance and composition (Exley *et al* 2022, Li *et al* 2023). Moreover, the magnitude of biological impacts will be highly dependent on the FPV design and coverage (Haas *et al* 2020, Exley *et al* 2022). For example, insulated structures installed across large footprints, where no wind or light penetrates, would be expected to be more impactful than freestanding structures with small footprints and gaps between the panels' rows.



3.3. Future research priorities

The existing evidence on FPV impacts and current understanding of water body function suggests the potential for various TES arising from FPV. However, evidence of the extent to which these will be realised is relatively limited. Moreover, the TES framework focuses on expanding potential benefits of coupling, in this case, FPV and water bodies, as an approach to increase its sustainability. Nevertheless, it is key to take into consideration the technology's potential risks to the environment prior to its deployment. Below, we summarise the areas where more understanding is required and highlight key research themes, mapping current knowledge on the environmental impacts of FPV.

There is a critical need for more extensive research effort on FPV impacts to develop understanding that can inform location, design and management decisions at a pace that matches the rate of deployment. The systematic review and subsequent snowball search reported here revealed 92 papers, although the rise has been exponential (figure 2). Whilst the majority of research articles we found report primary research, only 23 studies included empirical data, and of the 53 modelling-based studies, only three incorporated empirical data. Thus, more empirical data are critically needed; without more empirical data, well established water body models to simulate impacts cannot be robustly parameterised or verified. Furthermore, studies that assess water body impacts before and after FPV installation are urgently required (in our review, only eight such papers were found), ideally in a before-after control-impact design to account for the influence of other environmental drivers.

Ideally, future empirical studies should assess a suite of parameters using standardised methods to enable comparison across studies and analysis of interactions and cascading effects, for example investigating physical characteristics of the reservoir, such as thermal stratification, together with chemical and biological components, e.g. nutrient and plankton concentration. This would also enable more robust modelling, validated by the empirical data. To date, out of the 422 pieces of evidence from the 92 papers found, 67% related to physical, 23% to chemical, and 10% to biological impacts of FPV (figure 3). Impacts on evaporation, water temperature and plankton concentrations or biomass, were relatively well studied with strong agreement in the direction of change (SI 1 figure S2). In contrast, much more research effort is required for chemical and other biological impacts, especially in light of the complexity of the conditions and processes that govern the outcomes (Haas *et al* 2020, Exley *et al* 2022). Specifically, the effect of FPVs on deeper water temperature is less clear than that on near-surface temperature, and further assessments of the former would be valuable. To date, the chemical impacts of FPVs have been investigated individually rather than in a holistic manner; this is an important research gap, together with a lack of understanding of FPV impacts on different nutrient fractions, a lack of knowledge about such impacts in larger reservoirs, and a need for modelling assessments of impacts on this aspect of water quality. As such, integrated, ecosystem scale investigations are needed to fully assess the risks and potential for TES arising from FPV deployment.

Given the pervasive impacts of climate on water body processes and properties, future research should include studies within different climatological regions and in water bodies with different characteristics, as well as where FPV growth is expected. Current knowledge is not well distributed globally (figure 4) and evidence is critically required from equatorial climate zones, but also from arid and warm temperate zones, i.e. Europe and Asia, as, whilst there are several studies, high FPV growth is anticipated because land scarcity is a growing issue (Nobre *et al* 2024). Regions typified by low rainfall and high evaporation rates, even at seasonal scales, are attractive for FPVs in terms of evaporation benefits as well as energy production (Haas

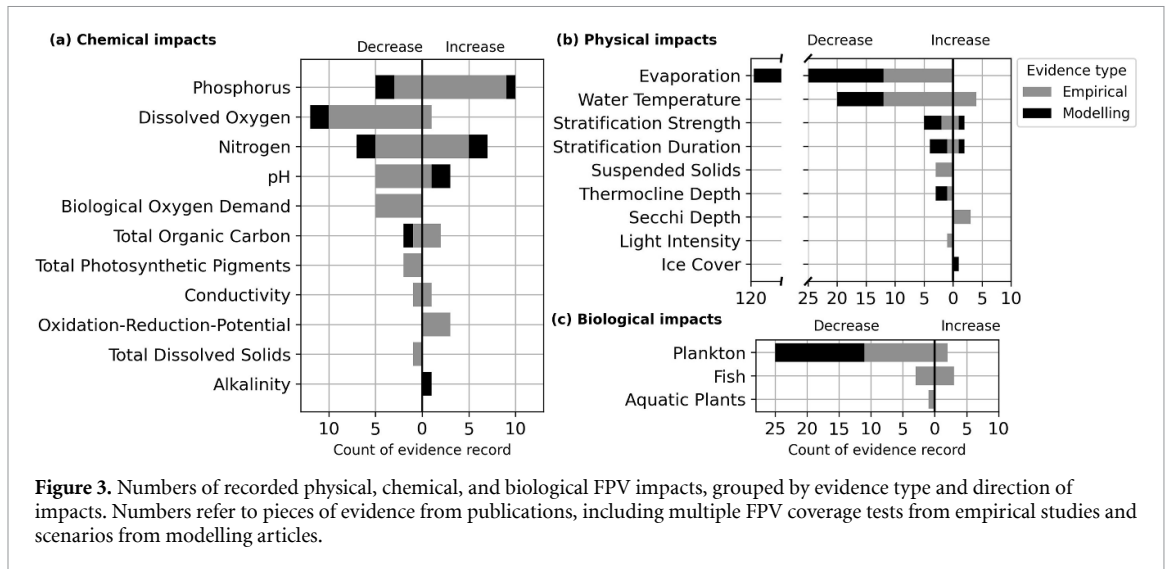
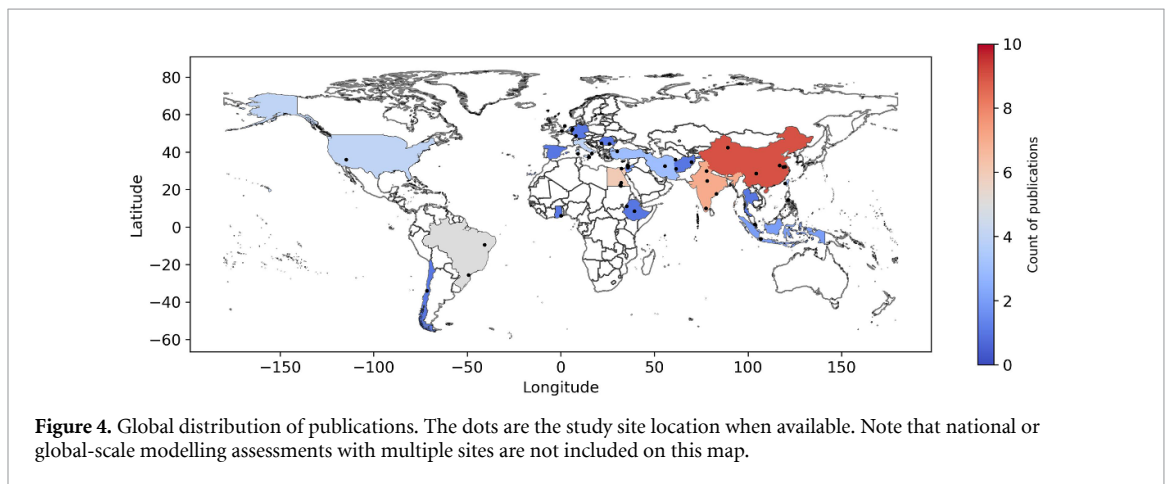


Figure 3. Numbers of recorded physical, chemical, and biological FPV impacts, grouped by evidence type and direction of impacts. Numbers refer to pieces of evidence from publications, including multiple FPV coverage tests from empirical studies and scenarios from modelling articles.



et al 2020, Kumar and Kumar 2020, Scavo *et al* 2020, Gonzalez Sanchez *et al* 2021, Majumder *et al* 2021, Ateş 2022). Such water bodies are likely to experience larger impacts from FPV deployment as warmer waters show steeper density gradients when compared to colder waters for the same temperature difference. Furthermore, any FPV impacts in higher latitude water bodies are likely to be highly seasonal (Château *et al* 2019, Ziar *et al* 2020, Ji *et al* 2022). Developing more understanding of the variations of FPV impacts across different water body types, would be valuable when evaluating FPV location and design decisions.

As well as developing understanding for climate zones where FPV growth is anticipated, future studies should focus on the water body types most likely to host them. The majority of existing studies were undertaken on dammed reservoirs ($n = 48$), likely reflecting their perceived lower ecological value, in addition to the existing management and infrastructure which may result in relatively easier installation and approvals processes (Spencer *et al* 2019, Ma *et al* 2021). Hydropower reservoirs were particularly prevalent ($n = 29$), which is to be expected given the existing power infrastructure at these locations (Haas *et al* 2020, Ferraz De Campos *et al* 2021, Gonzalez Sanchez *et al* 2021, Agrawal *et al* 2022), which can reduce costs and result in an improved power curve and increased efficiency (Ferraz De Campos *et al* 2021, Gonzalez Sanchez *et al* 2021, Mamatha and Kulkarni 2022). However, given the potential growth in FPV and consequences for ecology, understanding should also be developed for natural water bodies, as they support relatively greater biodiversity and thus, may be at greater risk from FPV-driven impacts.

The effect of a range of FPV designs, and in particular water body coverages, should also be assessed. Existing studies focused on FPV coverages from around 0.1% on bigger reservoirs (Santos *et al* 2020, De Campos *et al* 2021) up to 100% in modelling scenarios (Perez *et al* 2018, Exley *et al* 2022, Ji *et al* 2022, Moraes *et al* 2022) and smaller scale water bodies (Santafé *et al* 2014, Kumar and Kumar 2020, Li *et al* 2020, Abdelal 2021). Ideally, a combined empirical and modelling approach would define acceptable limits to coverages for a range of water body types and locations.

In summary, for many potential FPV impacts upon in-lake physical, chemical, and biological processes we currently lack evidence. Furthermore, the evidence that we do have is geographically heterogeneous. This limited evidence base underscores an urgent need for further investigation before robust general insights and ecosystem-scale understanding can be achieved. This work is essential for resolving desirable and undesirable outcomes, and the potential to realise TES.

4. Conclusions

This study provided an integrated consideration of energy and ecological processes by assessing the TES of FPVs. We identified eight TES potentially realised through FPV location, design, and operation decisions at the water body scale, those being: climate regulation, fuel diversity, food system resilience, human health and well-being, land sparing, PV module efficiency, water use efficiency, and water quality. Whilst this is a significant and timely contribution, further evidence through inclusion of additional research as it is published and extending the search beyond English language studies, will strengthen the insights. Extensive research is required to assure FPV deployments also deliver benefits for ecological systems; there was only sufficient aligned evidence for evaporation ($n = 114$ pieces of evidence) to reliably infer outcomes and the majority of the studies focused on the physical aspects of FPV impacts ($n = 283$), followed by chemical ($n = 96$) and biological ($n = 43$) aspects, respectively. This reflects the complexity of chemical and biological components, and indicates the urgent need for further understanding. Since each water body is a unified system where all of these components interact with each other, there is a clear need for integrated assessments of physical, chemical, and biological impacts upon water bodies.

Future research should measure and analyse multiple parameters simultaneously, such as water temperature, DO, nutrient and plankton concentrations and compositions, and seek to employ standardised approaches to these measures. Studies underpinned by high-quality empirical data will provide a basis for scenario testing using modelling, to investigate the effect of different FPV designs, especially coverage extent, and water body characteristics. Research should also target locations where deployments are expected to be extensive and where there is limited knowledge. If understanding of the water body impacts of FPVs keeps pace with FPV deployment rates, the opportunity to deliver environmental benefits alongside climate change mitigation can be realised.

Data availability statement

No new data were created or analysed in this study.

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Conflict of interest

The authors report there are no competing interests to declare.

Author contributions

Sofia M G Rocha: Conceptualisation, Data curation, Formal Analysis, Investigation, Methodology, Visualisation, Writing—Original Draft, Writing—Review & Editing; **Alona Armstrong:** Conceptualisation, Methodology, Supervision, Validation, Writing—Review & Editing; **Stephen J Thackeray:** Conceptualisation, Methodology, Supervision, Validation, Writing—Review & Editing; **Rebecca R Hernandez:** Writing—Review & Editing; **Andrew Folkard:** Conceptualisation, Methodology, Supervision, Validation, Writing—Review & Editing.

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